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Research article

Effects of atmospheric-plasma system on energy efficiency improvement and emissions reduction from a diesel engine

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ABSTRACT

Efficient energy usage and energy saving is one of the nowadays necessity for all scientists of IC engine. This is because of the current environmental challenges that have tremendously increased concerning air pollution, particularly pollutant emissions from vehicles. Yet, industries and governments alike have disregarded this phenomenon which has been considerably contributing to climate change. It is against this background that, the research works carried out in this present study is predominantly focusing on improving energy efficiency and reducing emission levels from diesel engines. This can be achieved with the help of atmospheric-plasma system which can offer a noble solution to the above-mentioned challenges due to its potential to improve combustion efficiency which leads to energy efficiency, while reducing emission levels from diesel engines. In this study, the performance and emissions of a diesel generator supplemented with an atmospheric-plasma system was examined. The diesel engine was used to examine the effects of fuel composition, or brake specific fuel consumption, thermal efficiency and pollutant emissions at different plasma system voltages. To this end, we equally examined the effects of atmospheric-plasma system on energy efficiency improvement and emissions reduction from diesel engine as the main purpose of this study. We do so by testing the diesel-fueled engine generator under the atmospheric-plasma system. The tests were carried out at a constant state condition with the engine running at 2200 rpm with torque and power outputs of 10.4 Nm (75% of the max load) and 2.1 kW, separately, for the tested fuels and this was used to increase the output voltage of the plasma system during this study. The plasma system ionized the intake air and improved the formation of free radicals upon combustion. During this study, the output voltage of the plasma was set within the range of 0–7 kV. The experimental results have indicated that formaldehyde, acetaldehyde and acrolein account for more than 75% of total carbonyl compounds emissions. Simultaneously, it was also observed from the results that higher plasma system voltage reduces pollutants emissions levels. Hence, such reduction is predominantly evident for nitrogen oxides, particulate matters and carbon monoxide. However, the marginal improvements of engine performance and emissions reduction become insignificant when the plasma system voltage reaches 6 kV. On the other hand, increasing the amount of plasma system voltages in diesel engine continues to significantly reduce pollutant emissions.

1. Introduction

Diesel fuel is used in internal combustion engines in many fields which include: automotives, engineering machinery, and marine propulsion (Ankur et al., 2016). The consumption of fossil fuels leads to various types of air pollutants such as nitrogen oxides (NOx), particulate matter (PM), carbon monoxide (CO) and other harmful substances. Moreover, around 60% of greenhouse gas emissions such as carbon dioxide (CO_2) are derived from the direct combustion of fuels (Ankur et al., 2016; Han et al., 2016; Wenwei et al., 2017; Jhang et al., 2018). Therefore, arises the need to replace part of the diesel fuel that is currently used with other alternatives.

Previous studies have pointed out the adverse effects of engine-out emissions on human health, greenhouse effects and environmental concerns such as toxic smog and acid rain. To limit the effects of exhaust emissions, several researches were completed to improve the

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diesel engine such as improving the design, influencing of structural and operating factors on performance degradation of the diesel particulate filter based on composite regeneration, optimization of the diesel particulate filter in the composite regeneration process, regeneration-diesel particulate filter based on NO_2 assisted regeneration (Zhang et al., 2017, 2016; Jiaqiang et al., 2016a,b; Liu et al., 2016; Xie et al., 2016), enhancing behaviors of the diesel particulate filter (DPF) in equilibrium state (Deng et al., 2017), installing catalytic converter, and alternative fuels from renewable-sources. Deng et al. (2018) studied the effects of cold start control strategy on cold start performance of the diesel engine based on a comprehensive preheat diesel engine model for better cold-start activity to simulate the characteristics of low temperature using Hardware-in-loop simulation technology, MATLAB/Simulink and FLUENT to obtain the related maps (preheat time, running speed, torque and so on) in China. Yet bio-fuels, such as biodiesel (Ankur et al., 2016; Debnath et al., 2013; Haldar etl., 2009; Han et al., 2016; Kousoulidou et al., 2010; Morais et al., 2010; Qi et al., 2011; Vivek and Kriplani, 2016; Wenwei et al., 2017) and bio-alcohol (Agathou and Kyritsis, 2011; Andrés et al., 2016; Chen et al., 2016; Lin et al., 2014; Rakopoulos et al., 2008, 2010), seem to be the most promising solution for clean engine operations. Biodiesel is one of the most credible modern-day alternatives to petroleum-based diesel as it is renewable, compatible with current economic and technological infrastructures and burnt cleanly. The fuel can be applied directly in most diesel engines through different technologies for combustion and emissions reason, and it has better performance than gasoline engines (Knothe et al., 2005; Pham et al., 2017; Liu et al., 2018). Biodiesel can simultaneously be applied to clean engine operations including marine diesel engines (Zhang et al., 2018), and reduce various engine emissions: carbon monoxide (CO), hydrocarbon (HC), particulate matters (PM), polycyclic aromatic hydrocarbon (PAH), polychlorinated dibenzo-p-dioxin/dibenzofuran (PCDD/F), and sulfur oxide (SO_2) (Khalife et al., 2017; Yang et al., 2015; Lin et al., 2011; Refaat, 2009; Salamanca et al., 2012; Saxena and Maurya, 2016; Tsai et al., 2015a,b; Pham et al., 2018). It similarly has a higher cetane number (Li et al., 2017; Lin et al., 2013; Sooknoi et al., 2008), which improves the combustion quality, higher flash point, and better lubrication properties than conventional diesel fuel. Biodiesel is the next-generation engine fuel that can meet the stricter emission regulations set by Environmental Protection Agency in the United States (Environmental Protection Agency, 2002). On the other hand, there remain several issues with biodiesel. Biodiesel has higher viscosity and higher pour point than conventional diesel fuel. It can also be oxidized more easily than diesel fuel. A typical resolution is to blend biodiesel with diesel fuel.

Contemporary studies revealed that butanol is a more appropriate alcohol for diesel engine applications. As compared to ethanol, the thermophysical and chemical properties of butanol, such as heating value, cetane number, viscosity and flash point, are more similar to conventional diesel fuel. However, butanol is almost perfectly miscible with diesel fuel, unlike ethanol. These properties render butanol as a preferable for blending with diesel, which can improve the properties of the blended fuel (Chotwichien et al., 2009; Huang et al., 2016). Even so, there is insufficient number of studies of butanol applications in diesel engines to reduce pollutant emissions (Chotwichien et al., 2009; Rakopoulos, 2013; Yang et al., 2015, 2016). Thus, the non-thermal plasma activation is a recent novel development in engine technology for after-treatment and emission control (Babaie et al., 2015; Okubo et al., 2004; Talebizadeh et al., 2014). Physically, plasma is an ionized gas characterized by very high electrical conductivity, generally considered as the forth state of matter. Plasma is basically a mixture of species, ions and electrons dissociated from atoms and molecules. The free-flowing electrons induce various reactions such as dissociation, ionization and enhance momentum transfer that alters the kinetic mechanism of ignition and combustion. Therefore, electron dissociation allows the easy cracking of fuel molecules into reactive species. Note that combustion is initiated by the breakdown of fuel molecules into active radicals (Jiaqiang et al., 2016a,b). Non-thermal plasma can therefore enhance the combustion process, and, it has been shown to alter flame behavior, activating combustion species (fuel and oxidant) and converting fuel-air mixtures into hydrogen and carbon monoxide (Bromberg et al., 1998; Du et al., 2016; Heywood, 1988).

Although there are extensive studies of non-thermal plasma applications in after-treatment of engine exhaust, there are only a limited number of studies on combustion control, flame stabilization and improving combustion efficiency in diesel engines (Cheruyiot et al., 2015; Mwangi et al., 2015; Najafi et al., 2016; Yang et al., 2017; Jhang et al., 2018). Atmospheric-plasma systems have been developed in response to a number of issues. The plasma system is designed to produce a uniform plasma cloud that fully surrounds small objects or spreads into the boundary layer of the surface. It can similarly be placed in the internal cavities, channels, and so on. The same plasma system can treat the internal surfaces of a 50-μm capillary and cover a 50- mm diameter (and higher) surface area. For example, one design of a machine is based on the well-known physical phenomenon (Ebnesajjad, 2011). The system is practically noiseless, produces very little ozone when operating in the open air, and generates no ozone when inert gases are used. Plasma technology contributes to the complete substitution of old energy-intensive manufacturing processes with new processes. For instance, the drying stage in conventional, wet chemistry processes consumes more energy as compared to the dry one, inline plasma process (energy-efficient surface pretreatment), thus, plasma technology is imminent for resource and energy efficiency (Plasmatreat, 2018).

The overall aim of this study is to investigate the effects of atmospheric-plasma system on energy efficiency improvement and emissions reduction from diesel engine. This is done by developing an atmospheric-plasma system technique that uses non-thermal plasma to increase the free radicals of intake air, while at the same time effectively enhancing the combustion efficiency (of the diesel engine) and reduce pollutant emissions from the diesel engine, thus saving energy or fuel due to the capability of atmospheric-plasma system application to improve combustion efficiency in diesel engine. We do so by testing the diesel-fueled engine generator under the atmospheric-plasma system. The atmospheric-plasma system was installed in the intake of diesel engine and a series of experiments were conducted using atmospheric-plasma systems with different voltage. The experimental setup is shown in Fig. 1. The tests were carried out at a constant state condition with the engine running at 2200 rpm with torque and power outputs of 10.4 Nm (75% of the max load) and 2.1 kW, separately, for the tested fuels and this was used to increase the output voltage of the plasma system during this study. The plasma system ionized the intake air and improved the formation of free radicals upon combustion. During this study, the output voltage of the plasma was set within the range of 0–7 kV.

2. Methods and materials

2.1. Test fuels and diesel-fueled engine generator

During this experiment, an air-cooled four-stroke diesel engine and its engine configuration is presented in Fig. 1, with its parameters presented in Table 2. Tests were carried out at a constant state condition with the engine running at 2200 rpm with torque and power outputs of 10.4 Nm (75% of the max load) and 2.1 kW, separately, for the tested fuels. A plasma system, from the Shinnchyuan Electric Work Ltd, was used in conjunction with voltage transformer, which was used to increase the output voltage of the plasma system during this study. The plasma system ionized the intake air and enhanced the formation of free radicals upon combustion. Throughout this study, the output voltage of the plasma was set within the range of 0–7 kV. This experiment uses a general-purpose diesel engine generator, which is manufactured by Yanmar Corporation of Japan (model L100N5/6-G(E)Y), and the diesel engine generator is shown in Fig. 1. The operation mode and the test

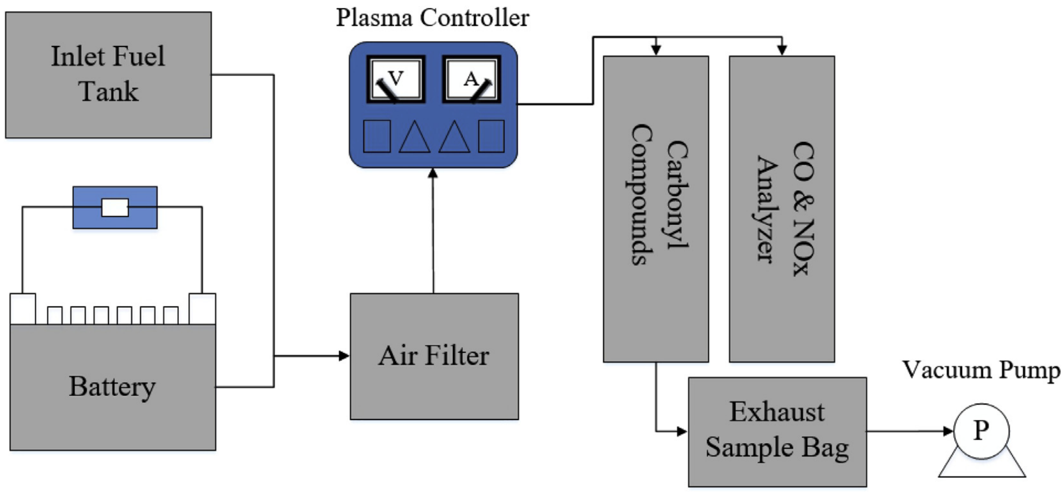


Fig. 1. A schematic of the experimental setup.

diesel engine was a four-stroke cycle type with four (4) cylinders, and the dimensions (L x W x H) of 720 × 480 × 578 mm, bore and stroke of 86 mm × 70 mm, fuel tank capacity of 13 L, with a diameter of less than 600 mm (24 inches). While the displacement volume is 435 cc, maximum output power is 6.6 kW at 3600 rpm and a decibel level of 1 m = 96 db; 7 m = 85 db. Testing was conducted according to FTP-75 (US Federal Test Procedure). The FTP75 has been used for emission certification of light duty vehicles in the US. The diesel engine is a natural air intake type, and the fuel injection type of the diesel engine is a direct injection, and the cooling method is water-cooling. The specifications are shown in Table 2. The diesel engine flue gas collection in this study was in accordance with the US federal test procedure, and an exhaust dilution channel was installed in the exhaust tail pipe. The exhaust dilution channel primarily provides a fixed and standard dilution ratio for the measurement of conventional contaminants (CO, NO_x), aerosols (PM_{10}, $PM_{2.5}$) and aldehydes and ketones. Before the first experiment was conducted, the engine was adjusted at the laboratory of the manufacturer following the factory specifications such as injection timing, fuel consumption rate, exhaust emission, etc. Prior to each set of experiment, the system, including gas tank, fuel filling system, cylinder, and the manifold of inlet air and exhaust, was first cleaned, followed by a dirty-up procedure. Furthermore, both the lubricating oil and the oil filter were changed and the fuel tank was emptied. The used plasma systems were from Shinnchyuan Electric Work Ltd. The experimental setup is shown in Fig. 1.

The performance of diesel engines is greatly influenced by their injection system designs. In fact, the most remarkable advances achieved in diesel engines resulted directly from superior fuel injection system designs. Although the main purpose of the system is to deliver fuel to the cylinders of a diesel engine, it is how that fuel is delivered that makes the difference in engine performance, emissions, and noise characteristics (Khair and Jääskeläinen, 2013; Bosch, 1971). Unlike its spark-ignited engine counterpart, the diesel fuel injection system delivers fuel under extremely high injection pressures.

In order for the engine to effectively make use of this fuel must be injected at the proper time, that is, the injection timing must be controlled and the correct amount of fuel must be delivered to meet power requirement, that is, injection metering must be controlled. However, it is still not enough to deliver an accurately metered amount of fuel at the proper time to achieve good combustion. Furthermore, other characteristics are critical to ensure proper fuel injection system performance, including fuel atomization and complete evaporation of fuel, ensuring that the evaporated fuel has sufficient oxygen during the combustion process is similarly as significant to guarantee high combustion efficiency and optimum engine performance. The oxygen is provided by the intake air trapped in the cylinder and a sufficient amount must be entrained into the fuel jet to completely mixed with the available fuel during the injection process and ensure complete combustion (Stanfel, 2009). The fuel injection system of a diesel engine plays a crucial role in reducing exhaust emissions by determining the spray formation ignition and combustion (Pilusa et al., 2012; Corkwell et al., 2003).

The base fuels used or tested were diesel, biodiesel and n-butanol. Tests were made for blends of butanol and diesel (Bu-D), biodiesel and diesel (B-D), and butanol and biodiesel (Bu-B), at different concentrations, while avoiding the use of emulsifiers (Lapuerta et al., 2017). The main properties of the three fuels used to prepare the blends are shown in Table 1. It should be noted that, despite the large differences between most of their properties, the derived cetane numbers are very similar for both diesel and biodiesel fuels, which permitted to concentrate the study on the effect of alcohols, rather than in that of the base fuels.

2.2. Sample collection

The engine emission from tail pipe is monitored online using a

Table 1
Properties of the fuels used.
Source: Lapuerta et al. (2017).

Parameters	Method	Diesel	Biodiesel	n-Butanol
Purity (%, v/v)	–	–	–	> 99.5
Density at 15 °C (kg/m^3)	EN ISO 3675	842.0	883.5	811.5
Kinematic viscosity at 40 °C (cSt)	EN ISO 3104	3.00	4.19	2.27
Higher heating value (MJ/kg)	UNE 51123	45.77	40.19	36.11
Lower heating value (MJ/kg)	UNE	42.93	37.64	33.20
C (wt %)	–	86.74	77.08	64.86
H (w %)	–	13.26	11.91	13.51
O (w %)	–	0	11.00	21.62
Water content (ppm wt)	EN ISO 12937	41.70	352.10	1146
Molecular weight (kg/kmol)	–	208.20	291.26	74.12
Boiling point (°C)	ASTM D86	149–385	190–340	117.4
Standard enthalpy of vaporization (kJ/kg)	–	–	353.56	645.47
H/C atomic ratio	–	1.83	1.85	2.50
Stoichiometric fuel/air ratio	–	1/14.51	1/12.50	1/11.15
CFPP (°C)	EN 116	−20	−1	< -51
Lubricity (WS1.4) (μm)	EN ISO 12156-1	371.45	1057	571.15
Derived cetane number	ASTM D7668-14	52.65	52.48	15.92

Table 2
Specific parameters of the engine.

Model	L100N5/6-G(E)Y
Engine Type	Four Strokes
Aspiration Type	Natural Aspiration
Fuel Injection System/Combustion System	Direct Injection
Cooling System	Water-Cooling System
Number of Cylinder	4
Fuel Tank Capacity	13 L
Dimensions L x W x H (Recoil) mm	720 × 480 x 578
Net Weight	110 kg
Bore × Stroke	86 mm × 70 mm
Displacement Volume	435 c.c.
Rated Engine Speed	6.6 kW @ 3600 rpm
Maximum Torque	10.4 Nm @ 2200 rpm
Decibel level	1 m = 96 db; 7 m = 85 db

portable gaseous pollutant analyzer (Telegan Sprint V4). Specifically, nitrogen oxide for each sample was analysed using a CLD (chemiluminescent detection) (model 404 Rosemount, UK). Carbon monoxide was detected using a NDIR (nondispersive infrared detector) (model 880A, Rosemount, UK). A detector flow isokinetic consoles system equipped (APEX INSTRUMENTS XC-572, and PM_{10} & $PM_{2.5}$ cyclone kit, USA) with quartz fibre filters (Pallflex® Tissuquartz 2500QAT-UP, 47 mm diameter) was installed on the downstream side of the diesel generator exhaust for particulate matters (PM_{10} & $PM_{2.5}$) collection. The system could automatically tune pump flow rate by a set of pitot tube to fit the monitored flow rate of exhaust gas from engines. Each filter sample was weighed by using an electronic analytical balance with fully automatic calibration technology (AT200, Mettler, Switzerland) to determine the net volume of collected PM.

3. Results and discussions

3.1. Engine performance

Brake specific fuel consumption (BSFC) and Brake thermal efficiency (BTE) are the most important parameters that measure the performance of diesel engine. In all cases, diesel fuel shows the lowest BSFC as compared to butanol-biodiesel blends. The BSFC was lowered as the voltage of plasma system increased as seen in Fig. 2. The mean BSFC of 122.6–134.8 g/kWhr for diesel was obtained. The plasma system was placed at the air intake of the engine and ionized air was inducted into the combustion chamber. When the voltage of plasma system is in the range of 4–7 kV, the results indicate that the plasma system induced more complete combustion, which in turn improved the fuel consumption and reduced the BSFC (Gosai and Nagarsheth, 2016). The fluctuations in BSFC values detected in this study are consistent with those reported by other studies (Jhang et al., 2018; Environmental Protection Agency, 2002; Schwab and Bagby, 1987). Comparatively low calorific values, high viscosity and high density in diesel engine might be responsible for slight upsurge in BSFC value (Lin et al., 2013; Jhang et al., 2018). But nevertheless, this challenge may be fixed with better vaporization of fuel mixtures, engines running at full load or high loads, or intake air preheated (Graboski and McCormick, 1998). The BTE of the engine falls under the range of 37–42%, as shown in Fig. 3. With the voltage of plasma system, the BTEs were increased by approximately 3–4%, depending on the fuel composition and voltage applied. Higher plasma system voltage would improve the BTE. The combustion chamber geometry plays a significant role in producing the gas motion that supports the combustion process. It therefore, influences both emissions and efficiency, although usually soot emissions are most strongly impacted by geometry (Wu et al., 2012; Dorri et al., 2009). As a result of the complexity of the interactions between chamber geometry, in-cylinder flow, and the fuels sprays it is difficult to state general design rules that apply across the full range of light-duty combustion systems, ranging from open-bowl designs with practically inactive flow to re-entrant bowl designs that depend on strong flow swirl (Miles and Andersson, 2015).

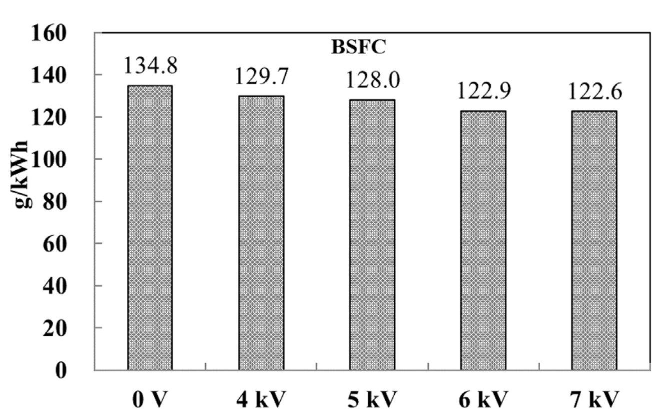


Fig. 2. Brake specific fuel consumption (BSFC) in different plasma system voltages.

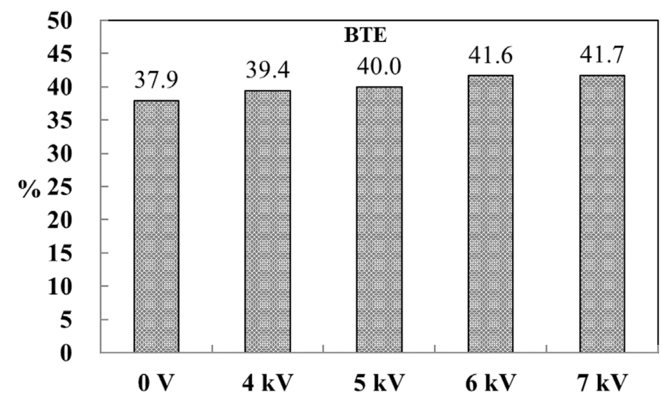


Fig. 3. Brake thermal efficiency (BTE) for diesel at different plasma system voltages.

3.2. Emission characteristics

The resultant sections describe about the emission characteristics of the diesel engine for the tested fuels with an atmospheric-plasma system.

3.2.1. NOx emissions

The emissions of NOx under different operating voltage of plasma in the diesel engine. Higher plasma voltage also lowered the NOx emission as shown in Fig. 4. The JME emulsion fuels produced lower NOx emissions due to the significant heat sink effect during the combustion

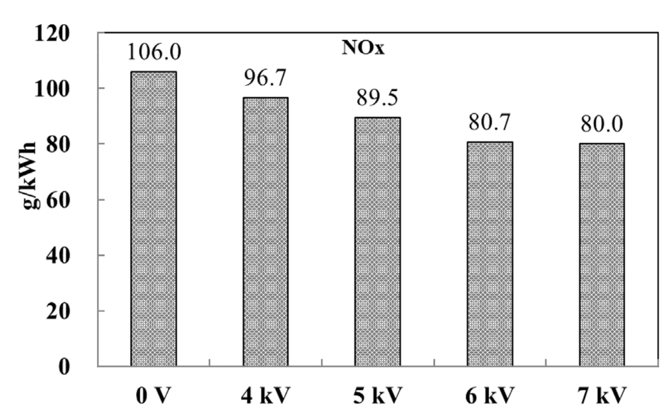
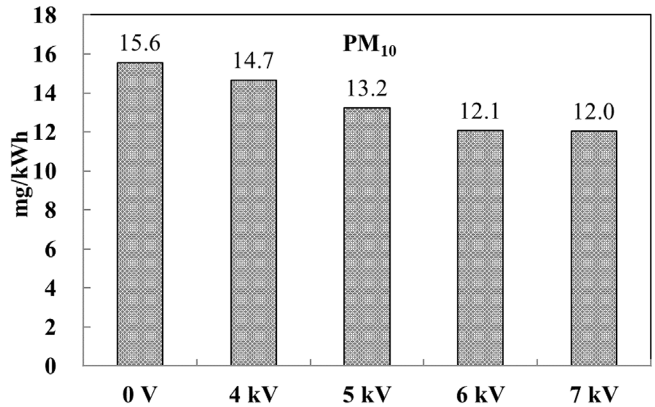
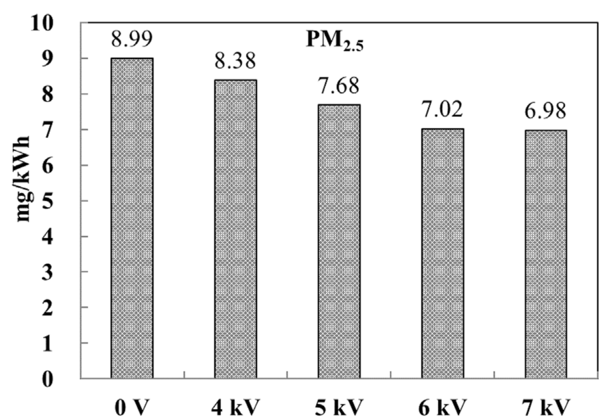


Fig. 4. NOx emission at different plasma system voltages in diesel engine.



(a) PM_{10} emission.



(b) $PM_{2.5}$ emission.

Fig. 5. Particulate emission at different plasma system voltages for diesel.

in the diesel engine. Due to the restricted lower temperature in the combustion chamber (as a result of vaporization), there could be a consequential dilution of gas species associated with the tested fuels and with an increased higher voltage, this could probably lead to reduction in the NOx emissions. Alternatively, this could be due to improved combustion, better homogenization of reactant mixture and reduced exhaust gas temperature (Basha and Anand, 2014). It can be seen that the average reductions in NOx is up to almost 25% with higher voltage of plasma (Sukjit et al., 2013). As a result, a longer ignition delay was expected, which pushed the combustion process well into the expansion stroke. Therefore, the results showed that using plasma system at inlet manifold can improve ionized air reduce the pollutant emissions.

3.2.2. Particulate matters

The level of PM10 and PM2.5 emissions under different operation conditions for the diesel engine, using different plasma voltages as shown in Fig. 5. The emission level was within the range of 12–16 g/kWhr and 6–9 g/kWhr for PM2.5. Higher plasma voltage has reduced the emission level. The results have revealed that up to approximately 25% decrease in PM10 and PM2.5 is feasible with high voltage to the plasma system. It is suspected that further increasing the voltage would not further reduce the emission level. The particulate emission level was lowered by increasing the plasma voltages. Note that particulate was mainly formed from incomplete combustion in locally-rich patches within the combustion chamber (Gosai and Nagarsheth, 2016).

3.2.3. Carbon monoxide and carbon dioxide emissions

The measured level of carbon monoxide under different operation conditions for the diesel engines under different plasma voltages as

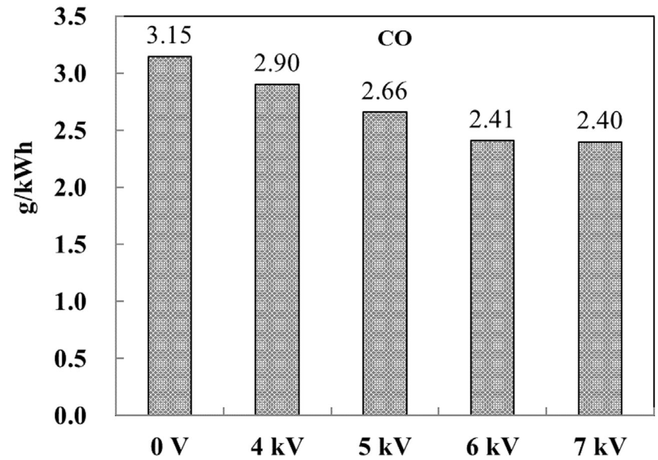


Fig. 6. Emission of carbon monoxide at different plasma system voltages for diesel.

shown in Fig. 6. Carbon monoxide is a product of incomplete combustion. The cooler environment impedes with the complete oxidation of carbon in to carbon monoxide (Lin et al., 2012). This causes a significant reduction of the carbon monoxide emission level observed in Fig. 6. The quantified emission was in the range of 2 and 3.5 g/kWhr. The emission was drastically narrowed due to higher plasma system voltage. It can be concluded from the figures that up to nearly 25% decrease is imaginable by means of 7 kV voltage to the plasma system. The results have revealed that ionized air can efficiently reduce carbon monoxide emission. But most remarkably, the emission levels for 6 kV and 7 kV were almost matching. It is therefore assumed that further increasing of voltage would not equally further decrease carbon monoxide emission. So as to say, the optimum voltage of the plasma system is 6 kV under the above-mentioned operation condition. It can also be concluded that, lowering diesel contents had resulted in reduced carbon monoxide emission. However, the measured level of carbon dioxide emission at different plasma system voltages for diesel engine are shown in Fig. 7. The results indicate that CO_2 emission increased with high plasma system voltage, with the emission levels for 6 kV and 7 kV reaching 113.4 g/kWhr.

3.2.4. Carbonyl compounds emissions and profiles

The composition of carbonyl compounds in the exhaust emissions for diesel engine. The engine was operating without the plasma system as shown in Fig. 8. Note that formaldehyde, acetaldehyde and acrolein account for 75–90% of total carbonyl emissions, depends on fuel mixture composition. No other species, with the sole exception of propionaldehyde, accounted for more 10% of the carbonyl emissions from the

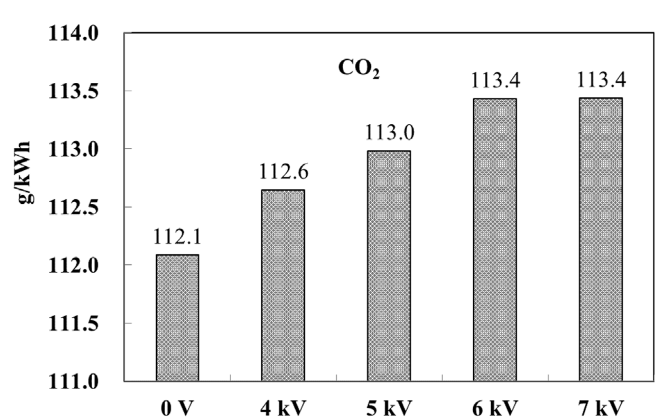


Fig. 7. Emission of carbon dioxide at different plasma system voltages for diesel.

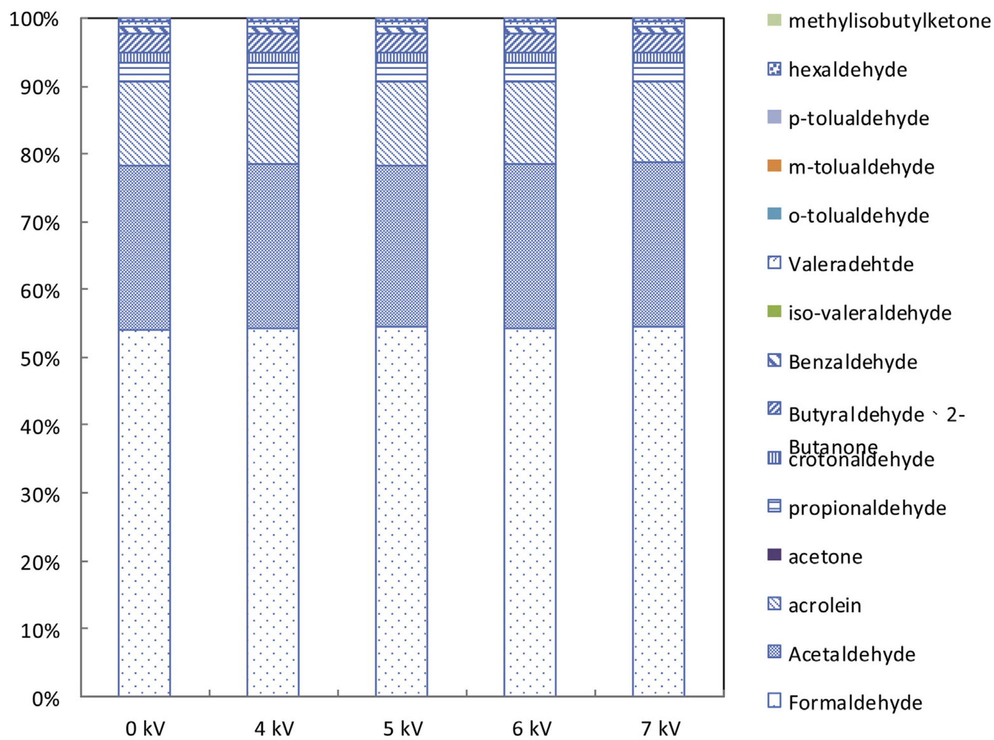


Fig. 8. The profile of carbonyl emission from diesel engine operating with the plasma system.

engine. Previous studies have shown that formaldehyde, acetaldehyde and acrolein are the dominant carbonyl compound in diesel engine emission as well (Jhang et al., 2016; Lü et al., 2016).

3.3. Carbonyl compounds emissions factors

The fifteen carbonyl (CBC) compounds were detected in the experiments, including formaldehyde, acetaldehyde, acrolein, propionaldehyde, crotonaldehyde, butyraldehyde and 2-butanone, benzaldehyde, valeradehtde and hexaldehyde are shown in Table 3. The three major CBC species in diesel emission were formaldehyde (about 62%), acetaldehyde (about 27.5%), butyraldehyde and 2-butanone (about 3%). The three-major species accounted for about 92% of total CBC compounds in the emissions. The effects of applied voltage in the plasma system had no visible effects on the composition in the CBC emission. As the applied plasma system voltage increased to 4 kV, the change in CBC emissions became 1.38%, 2.17%, 6.26% and 14.3% for diesel engine. The figures become 2.06%, 1.74%, 6.56% and 14.4% for 5 kV of applied plasma system voltage, and, 1.99%, 1.52%, 6.39% and 14.3% with 7 kV of applied plasma system voltage. This shows that the voltage of the plasma system does not affect the CBC emission composition, experimental measurement shows raising the applied voltage can lower the emission level from the diesel engine. For example, the total CBC emissions were reduced by about 5%, 8%, 12% and 12.5% when the voltage was increased from 0 kV to 4 kV, 5 kV, 6 kV and 7 kV, respectively. These results show that the effect of higher voltage saturated at 6 kV of voltages applied to the plasma system. Higher plasma system voltage also lowered the Acrolein emission level slightly, but the reduction was insignificant (see Table 4).

Table 3
Comparison of an atmospheric plasma and a 3D corona-treater.
Source: Ebnesajjad (2011).

	Atmospheric plasma	3D Corona
Average power	100 W	1000 W
Plasma carrier	Argon	Air
Plasma currents	Low (mA)	High (10 mA)
Main direction of the energy transfer	From the electrode to the substrate surface	Between the electrodes parallel to the substrate surface
Plasma frequency	High (20,000 Hz)	Low (60 Hz)
Noise level	Low	High
Ozone generation	Low	High
Plasma flow temperature	Low (room)	High (> 250 °F)
Substrate exposure	Unlimited	Limited to thermal damage
Coverage from single head on the flat surface	Up to 3-in-diameter circle or up to 5 in × 1 in strip	Up to 2 in × ¼ in strip
Ability to treat patterned surfaces	Unlimited	Limited
Ability to treat inner surfaces	Unlimited	Very limited
Ability to introduce special additives into the plasma for chemical surface modification	Limited	Very limited
Overall flexibility	High	Low
Overall efficiency	High	Low

Table 4
The carbonyl emission concentration from diesel engine operating with the plasma system.

$\mu g/m^3$	0 kV	4 kV	5 kV	6 kV	7 kV
Formaldehyde	2835	2693	2636	2509	2494.8
Acetaldehyde	1273	1203	1160	1112	1107.8
acrolein	650	600	595	560	545
acetone	–	–	–	–	–
propionaldehyde	148	141	138	132	129
crotonaldehyde	75	71	69	66	65
Butyraldehyde、2-Butanone	153	145	142	135	134
Benzaldehyde	45	43	42	40	39
iso-valeraldehyde	–	–	–	–	–
Valeradehtde	39	37	36	34	34
o-tolualdehyde	–	–	–	–	–
m-tolualdehyde	–	–	–	–	–
p-tolualdehyde	–	–	–	–	–
hexaldehyde	31	29	28	27	27
methylisobutylketone	–	–	–	–	–
Total emissions	5249	4962	4847	4615	4577

3.4. Experimental uncertainty and error analysis

In this study, the combustion parameters are derived from in-cylinder pressure measurement and analysis. The cycle-to-cycle variations in these parameters have been given in reference (Sergi et al., 2016; Parbhoo, 2006). Uncertainties in the measurement of different measured quantities are analysed. Table 5 provides the range, accuracy, and percentage uncertainties of various instruments used in this experiment for observing various parameters. Errors and uncertainties in the experiments may occur as a result of the selection of instrument, working condition, calibration, environment, observation and method of conduct of the tests (Sergi et al., 2016). Uncertainty analysis was necessary to prove the accuracy of the experiments. The percentage uncertainties in measuring various parameters were determined using the root-sum-square method (Sergi et al., 2016; Parbhoo, 2006). The percentage uncertainty of various instruments used in the experimental investigation and the error analysis of the results are shown in Table 5.

For this experiment,

$$\begin{aligned}&\text{Total percentage uncertainty}\\&= [(\text{uncertainty of TDC})^2 + (\text{uncertainty of pressure sensor})^2\\&+ (\text{uncertainty of temperature indicator})^2\\&+ (\text{uncertainty of air flowrate measurement})^2\\&+ (\text{uncertainty of fuel flowrate measurement})^2]^{1/2}\\&= (0.2^2 + 0.1^2 + 0.15^2 + 1^2 + 0.2^2)^{1/2}\\&= \pm 1.1\%\end{aligned}$$

4. Research gaps and future perspective in the application of atmospheric-plasma system

A rising number of research studies are published in the literature increasing our understanding of plasma chemistry in the engine exhaust gases. However, this technology has still a novel character and existing results requires to be assessed with due diligence. Since many studies are conducted in small scale laboratory experiment, as opposed to a full-flow engine experiment, inconsistent interpretation of data is normally doubtful. It is very easy to overlook a formation of anonymous chemical compounds in the plasma or to complicate adsorption and storage of material in the test equipment with its steady-state removal. With regards to vehicle plasma applications, it is very critical to make a dissimilarity between NO removal by chemical oxidation and NO removal by chemical reduction (Ebnesajjad, 2011; Parbhoo, 2006). The anticipated inclusive process is chemical reduction to environmental-friendly products, such as nitrogen and oxygen. In the preceding literature on plasma processing, several authors applied the term “NO reduction” even when the NO removal is achieved by oxidation to NO_2 and nitric acid. It is not adequate for the experimental plasma work to record a reduction in terms of concentration of the NO or NOx. This is because probable reaction products may include many other nitrogen species which may be not acceptable. Several of these by-products may be also difficult to detect in the laboratory setup. Besides nitrous and nitric acids these products may include nitrates, nitrites or organonitrites which can be deposited on reactor walls, on particulates, or on the pellets material if a packed bed reactor is used. Even if chemical reduction of NO dominates, the products may include nitrous oxide N_2O which, although not a regulated emission, is not an acceptable product (Parbhoo, 2006). Commercialization of non-thermal plasma technology for emission control from mobile sources requires significant advancements and much more development work. The plasma may or may not become a viable choice for lean NOx or PM removal systems.

Table 5
List of instruments and their ranges, accuracies, and uncertainties.

Instrument	Range	Accuracy	Percentage uncertainties
Pressure sensor	0–250 bar	± 0.1	± 0.1
TDC sensor	–	± 1°	± 0.2
Shaft encoder	–	± 0.5°	± 0.1
Speed-measuring unit	0-1000 r/min	± 10	± 0.1
Manometer	–	± 1 mm	± 1
Temperature indicator (K-type thermocouple)	0–1000 °C	± 1 °C	± 0.15

4.1. Innovation with plasma technology: new applications for all areas of industry

The potential range of applications using plasma technology is unlimited. In several areas of industry, treatment with atmospheric pressure plasma is already firmly established. In other areas for instance, in life sciences and new forms of energy, but also in aviation and aerospace intensive research is being steered on new application solutions. Nowadays, there are already innovative accomplishments in protective coating of solar cells, the development of fuel cells, and innovative lightweight construction with carbon fiber materials. Initial tests in the treatment of human skin further demonstrate the extensive potential of plasma technology in future breakthroughs (Plasmatreat, 2018; Ebnesajjad, 2011).

4.2. Plasma treatment instead of wet chemistry: environmentally friendly energy savings using dry processes

Plasma technology under atmospheric pressure conditions, with its inline capability, makes it possible to fully redesign production processes (process optimization) in various industrial applications. Since the entire surface treatment process runs under dry conditions, it also provides the highest potential for energy saving. Whereas the drying processes that require a lot of energy are eliminated. In addition, the use and disposal of many toxic chemicals can be equally avoided. A technique for eliminating drying processes that has been effective for years is plasma coating of workpieces. Plasma coatings offers further functionalities and regularly can be applied at a fraction of the cost equated to conventional coating processes with painting, etc. So far, plasma coating was implemented in a low-pressure process, for example, with PVD and sputtering processes. Now with the plasma process, combined with plasma coating can be applied under normal pressure without separate chamber systems (Plasmatreat, 2018; Ebnesajjad, 2011).

4.3. Energy-efficient processes: plasma treatment means low processing temperatures and high process speeds

When diverse materials are combined, such as in bonding, laminating or painting, surface tension and surface cleanliness are critically significant for reliable adhesion. In order to accomplish good adhesion characteristics, the materials are often brought to a specific necessary processing temperature in the manufacturing process. Normally, these are very energy-intensive processes. In contrast, plasma treatment is not only an especially effective method for surface pretreatment, it is also an energy-saving alternative. The use of atmospheric plasma makes a definite reduction in operating temperatures possible in many applications. The heating process can usually be shortened or even eliminated completely. The same is true for drying ovens when alternative coating systems (like UV-curing systems) are used. An example of success in coil coating: By using plasma cleaning (ultrafine cleaning) and plasma activation, it is possible to use UV-curing paints. The complete system configuration is reduced to 25% of the scope of a conventional system (Plasmatreat, 2018; Ebnesajjad, 2011).

5. Economic analysis for the atmospheric-plasma application

The plasma technology makes it possible for industry to respond to continuously increasing demands on raw materials and materials efficiency, energy savings, and to avoid use of pollutants and chemicals. According to DEMEA (Deutsche Materialeffizenz Agentur [German Materials Efficiency Agency]), material costs represent the greatest share of costs by far, at approximately 45.4%, even ahead of personnel costs (Plasmatreat, 2018). Previously incompatible materials can be bonded to each other for the first time in industrial manufacturing by using plasma treatment technology. Alternative, more cost-effective, lighter or more stable materials or even recycled materials, can be used. A new freedom in materials usage is coming into being. Also, little commercial production has been experienced in developing countries of energy saving technologies like plasma technology, and thus their market value is not yet known. So, the cost analysis of the atmospheric plasma technology can be made only based on production cost. The cost that are taken into account include inline-capable, cost-efficient and environmentally friendly plasma processing at atmospheric pressure, the application oriented use of different plasma sources, e.g. dielectric barrier discharge (DBD), atmospheric pressure plasma jets (APPJs) etc., scalable technology for varying the treatment area and processing velocity, various process gases and deposition precursors for appropriate plasma based cleaning, activation and functionalization of surfaces and other supplies. Another important aspect that will affect the cost of the atmospheric-plasma technology application is cost development of the technology itself. All these aspects of atmospheric-plasma technology would be possible at the cost of around USD400.00. Furthermore, the technological developments for atmospheric plasma technology of excellent efficiency and great energy saving capability will be helpful in achieving lower atmospheric-plasma technology costs in the near future.

6. Conclusion

This study examined the operation of a diesel generator operating with a plasma system, at a different plasma system voltages. Experimental results show that formaldehyde, acetaldehyde and acrolein as the major components of carbonyl compounds (CBCs) emissions. The results also show that increasing the voltage of the plasma system reduces pollutant emissions and improve engine performance (lower BSFC and higher BTE), thus saving energy. However, as the effects of increasing voltage saturates at 6 kV - further raising the plasma system voltage does not improve the emission levels. Further effort can be invested in studying the application of a plasma system in an automotive diesel engine operating in different modes such as conventional combustion and homogeneous charge compression ignition. In the case of diesel exhaust a removal of particulate matter emissions would be also a valuable benefit of plasma systems. Plasma systems have been shown to be capable of reducing of diesel particulate matter by low temperature oxidation. However, it is not currently clear whether the NOx and PM control functions by plasma can be combined in one device, i.e., if NTP reactors can be designed for the simultaneous control of NOx and PM. Yet, plasma technology under atmospheric conditions, with its inline capability, makes it possible to completely redesign production processes (process optimization) in many industrial applications. Since the entire surface treatment process runs under dry conditions, it also offers the greatest potential for saving energy. Thus, the research findings in this paper will serve as a valuable reference for the development and application of the plasma system voltage to minimize pollutant emissions, improve engine performance and saving energy.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2019.01.017.

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